Additive Manufacturing: Opportunities and Challenges for Functional Magnetic Materials

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1 Introduction

Additive manufacturing (AM), also known as 3D printing, is transforming manufacturing due to a highly digital approach, the ability to near-net shape manufacture highly complex internal and external shapes of nearly any material, and targeted pore and grain microstructure (thus, properties). AM structural materials are already certified and used in many applications in fields like aerospace, automotive, architecture, medical and dental. However, AM of functional materials – especially magnetic shape memory and magnetocaloric materials – has yet to be developed as a manufacturing option. Early attempts of AM and AM-related methods such as inkjet printing, spark plasma sintering, laser melting, and binder jetting (e.g. [1-7]) show the challenges and opportunities of different approaches to increase the manufacturing envelope for functional magnetic materials. Here, binder jet 3D printing (BJ3DP) and laser metal deposition (LMD) were used to investigate the influence of printing and processing parameters on microstructure, impurities, and properties of Ni-Mn-based functional magnetic materials.

2 Experimental procedures

Powder was produced by crushing and ball-milling melt-spun ribbon (Ni-Mn-Co-Sn), polycrystalline ingots (Ni-Mn-Ga, Ni-Mn-Cu-Ga) and single crystals (Ni-Mn-Ga). The ball-milled powder was sieved to select size ranges optimal for BJ3DP and LMD. An Optemec LENS® 450 LMD system was used to (1) deposit layers onto Ni substrates, and (2) remelt or deposit onto single crystals. As-printed samples were characterized and compared to homogenized ones. BJ3DP samples (ExOne Lab) were sintered with different atmospheres, temperatures, and holding times to investigate microstructural evolution and sintering kinetics.

3 Results and disucussions

3.1 LMD: opportunities and challenges

Opportunities and challenges of LMD are depicted in Fig. 1. LMD of Ni-Mn-Ga shows twins and grains spanning printed layers, indicating potential for epitaxial growth. The ability to feed several powders and *in-situ* parameter tuning allows for gradient structures, which is beneficial for stress reduction at interfaces or graded composition/properties. Although microsegregation and dendritic microstructures were present in as-printed Ni-Mn-Ga and Ni-Mn-Co-Sn, homogenization eliminated the undesired structures (Fig. 2a-b). On the other hand, homogenization might lead to undesired recrystallization.

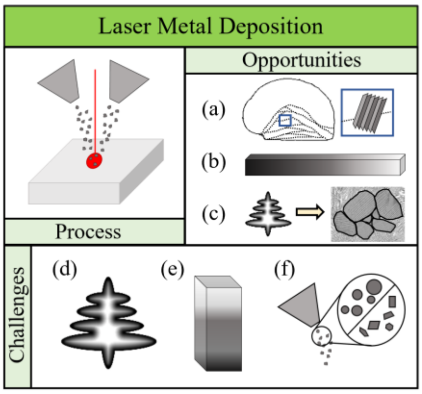

Figure 1: LMD has distinct opportunities and challenges including (a) grains grow epitaxially from substrate over multiple print layers, (b) gradient properties are possible, (c) heat treatment homogenizes samples; (d) Microsegregation and dendritic microstructure, (e) property variation, (f) powder feeding difficulties for non-spherical powder.

Gradient structures are desired in some applications, but variation of structure and properties within parts might be a challenge. The irregularly-shaped ball-milled powder is easily produced but shows inconsistent flow rates through the powder feeders and, therefore, inconsistent built shapes, unlike ideal spherical powder.

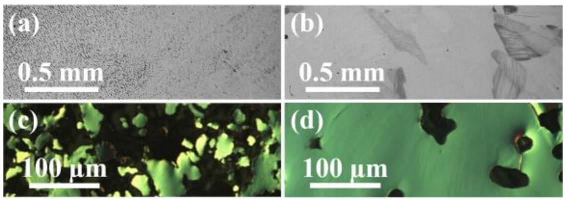

Figure 2: (a) LMD as-printed, (b) LMD homogenized, (c) BJ3DP sintering at 1020 °C, (d) 1080 °C.

3.2 BJ3DP: opportunities and challenges

BJ3DP is fundamentally different from LMD since powder is not melted during printing and therefore requires post-processing, i.e. sintering. By varying sintering parameters, bulk density can be varied (Fig. 2c-d) and shrinkage occurs. Though structural applications require high density, functional magnetic materials can benefit from porosity. By not melting the powder during printing the original composition of the powder remains intact, and residual thermal stresses are not developed.

Binder, powder, and shrinkage effects are identified as challenges. During binder deposition, the droplet can penetrate the bed differently depending on powder characteristics, as well as droplet size. Similar to LMD, irregularly-shaped powder is simpler to produce in small quantities and avoids some contaminations inherent in gas atomization, but spreads less predictably (Fig. 3).

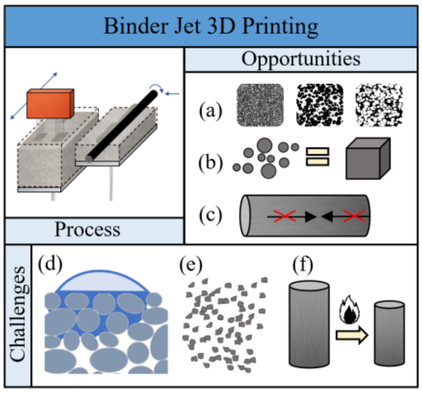

Figure 3: Major opportunities and challenges of BJ3DP are as follows: (a) controlled, multimodal porosity, (b) consistency of composition, (c) absence of thermal stresses; (d) binder effects, (e) powder challenges, (f) shrinkage during sintering.

Conclusions

While many challenges exist for each AM method discussed and not discussed here, there are also many advantages. Depending on the AM method, increased complexity in shape, the ability to design and target constant and gradient composition and properties and designed bi-modal porosity are a few of the new possibilities available. These benefits present the potential of expanding functional magnetic materials to new, currently impossible applications.

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Notes